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# Earth's Future

## RESEARCH ARTICLE

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### Key Points:

- We quantify five features of urban expansion among 220 watersheds globally for the last 25 years
- Most of the watersheds globally experienced a decelerating and sprawling urban expansion
- Rapid and low-density of urban expansion in endorheic watersheds may threaten their sustainability

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Patterns and Distributions of Urban Expansion in Global Watersheds

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**Abstract** Understanding urban expansion at the watershed scale is important because watersheds are important carriers of ecological and environmental impacts. However, current analyses are mainly restricted to administrative units only. Here, we used a long-term multitemporal data set of urban land to quantify the spatiotemporal trends in the extent and form of urban expansion from 1992 to 2016 in endorheic and exoreic watersheds, globally. Overall, urban expansion in 70% of watersheds (154/220) showed a decelerating trend. The average urban expansion speed of these watersheds in the last 6 years was approximately half of that in the last 24 years. Urban expansion speed in endorheic watersheds lagged behind the counterparts in exoreic watersheds, with the former approximately 1/4 of the latter. More importantly, the pattern of urban expansion in endorheic watersheds was following the low-density and sprawling trend in exoreic watersheds, which could exert far-reaching impacts on the sustainability of endorheic watersheds located in arid lands. These findings suggest the need to look beyond administrative city boundaries for land use planning and policies in the context of watershed management.

**Plain Language Summary** Urban expansion and its impacts are not restricted in urban boundary, but manifest at broader scales, such as watersheds. Previous studies mainly examine the characteristics of urban expansion from the perspective of administrative division, while a comprehensive understanding of the watershed scale is lacking. This study investigated five features of urban expansion (speed, trend, heterogeneity, mode, and efficiency) among thousands of watersheds globally, and compared these features between endorheic and exoreic watersheds. The results show that, globally, urban expansion slowed down in most of the watersheds. However, the unevenness and low-density development of urban land still dominated in both endorheic and exoreic watersheds. This study could provide a benchmark and proxy for measuring human activities and their environmental impacts at the watershed scale. It also calls for a governance shift from administrative boundary to watershed boundary.

## 1. Introduction

The world has experienced rapid urban expansion during the last few decades. In 2018, the global urban land area reached  $7.97 \times 10^5 \text{ km}^2$ , 1.5 times that in 1990 (Gong et al., 2020). The average annual increase in the urban land area reached  $9.7 \times 10^3 \text{ km}^2$  from 1985 to 2015 (Liu et al., 2020). In the future, urban land is expected to continue to expand, globally (Angel et al., 2011). It is estimated that by 2030, the global urban land area will be three times that in 2000 (Seto et al., 2012). While urban expansion provides opportunities for residents to improve their well-being, it also puts enormous pressure on the regional environment (Acuto et al., 2018; Elmqvist et al., 2019; Grimm et al., 2008). Therefore, characterizing the trend and mode of urban expansion is of great significance toward sustainable development.

Existing global studies mainly analyzed the process of urban expansion based on administrative divisions, focusing on comparisons between continents, countries, or cities. These studies provided valuable insights into the amount, speed, and trend of urban expansion in recent decades. For instance, North America and Asia showed the largest increase in terms of the total area of urban expansion (Gong et al., 2020; He et al., 2019). In terms of the speed of urban expansion, China and India ranked high (Güneralp et al., 2020;

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Seto et al., 2011). In terms of the changes in urban expansion speed, developing countries in Asia, Africa, and South America experienced accelerating urban expansion from 1985 to 2015, while developed countries in North America, Europe, and Australia started to slow down (Liu et al., 2020). Güneralp et al. (2020) revealed that the urban expansion speed in China exhibited a downward trend, while that in India exhibited an upward trend. Yet, because several important impacts of urban land relate to the hydrological cycle and biogeochemical cycle, assessing urban development within watersheds would provide a valuable addition to earlier findings for administrative regions. First, the amount and speed of urban expansion can indicate the level of human activities and their reliance on natural resources in a given watershed. Urban expansion relies on watersheds to continuously provide indispensable natural resources, for example, water resources and land resources (McDonald et al., 2011, 2014), for its prosperity. Such a quantitative measure of urban expansion at the watershed scale is still lacking, globally.

Second, urban expansion exerts in situ and far-reaching ecological and environmental impacts. It not only occupies natural habitat and threatens local biodiversity and food security (d'Amour et al., 2017; Elmqvist et al., 2013; Huang et al., 2018; Huang et al., 2020; McDonald et al., 2020; van Vliet, 2019; van Vliet et al., 2017), but also alter regional hydrological and biogeochemical cycles (Huang et al., 2019) and lead to increasing exposure risk to natural disaster, for example, storm surges (Fang et al., 2014), floods (Du et al., 2018; Güneralp et al., 2015), land-slides (Chen et al., 2019), and air-pollutant or water-pollutant discharge (Grimm et al., 2008). These ecological and environmental pressures call for a shift in governance from political boundaries to hydrological ones (Cohen, 2012). To avoid putting more people and economic assets at risk, the prevention and control of floods and other disasters need to be prevented and managed at the watershed scale (Mård et al., 2018). Correspondingly, the information on the differences in urban expansion among watersheds and heterogeneity of urban expansion within a watershed is indispensable for this governance shift.

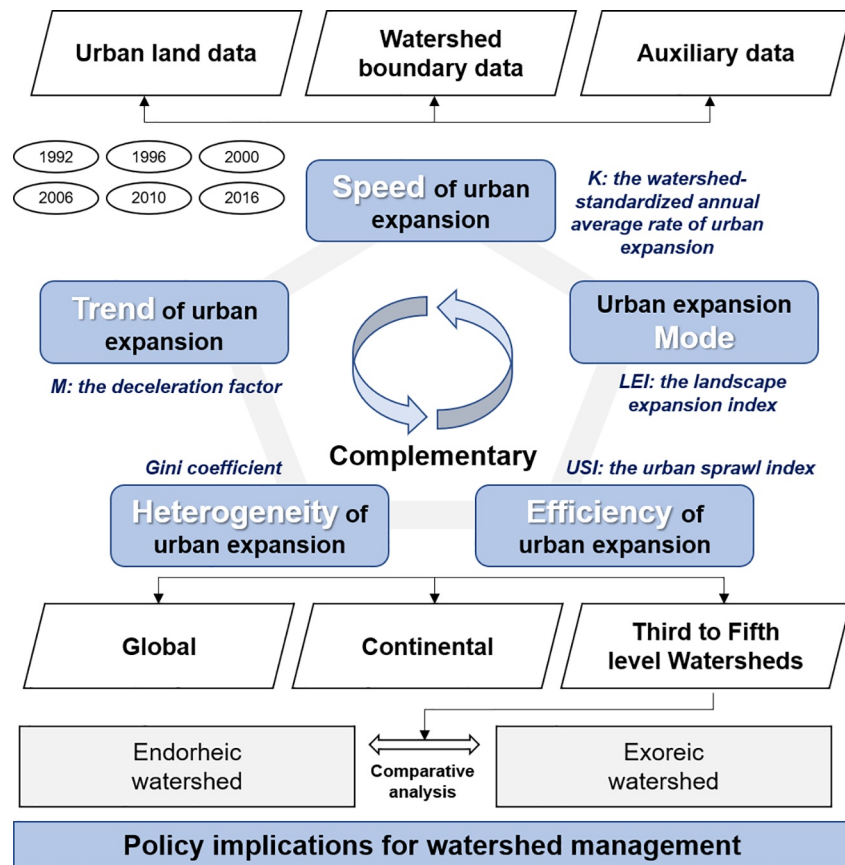
Third, urban expansion in some endorheic watersheds was catching up with exoreic watersheds in terms of its speed (Güneralp et al., 2015; He, Gao, et al., 2017; Luan & Li, 2021). Such rapid urban expansion in endorheic watersheds may render unprecedented pressures on local ecosystems and human well-being. This holds true specifically in those endorheic watersheds that are located in arid and semi-arid climates, and face the challenges of water resources shortage and vulnerability to extreme droughts and floods (Güneralp et al., 2015; Li et al., 2017; Prăvălie, 2016; Wang et al., 2018). In addition, urban expansion in endorheic watersheds is commonly restricted by topographic and hydrological conditions (e.g., steep mountains and groundwater sources), and resulted in leapfrog patterns of development and long-distant commuting. Consequently, urban expansion in these endorheic watersheds may manifest in a way of low-density and low-efficient form. Therefore, it is imperative to compare the trends, modes, and efficiency of urban expansion between the endorheic and exoreic watersheds, and inform decision-makers to plan for countermeasures.

This research analyzes the spatiotemporal dynamics of urban expansion among global watersheds and compares their characteristics between endorheic and exoreic watersheds (Figure 1). First, we quantified the amount and speed of urban expansion for five periods of the last 24 years based on the 1992–2016 global urban land data set. Then, we examined the differences in mode and efficiency of urban expansion between the endorheic and exoreic watersheds. Finally, we discussed the implications of the watershed-scale results and their potential applications in future studies.

## 2. Materials and Methods

### 2.1. Data

We used a global multitemporal urban land data set from 1992 to 2016 in this study (<https://doi.pangaea.de/10.1594/PANGAEA.892684>). In this data set, urban land is defined as the area with more than 50% in cover by non-vegetated, human-constructed elements, and this definition excludes rural settlements (He et al., 2019; Huang et al., 2020; Luan & Li, 2021). This data set provides urban land information at a 1 km<sup>2</sup> resolution extracted by deep learning, with an overall accuracy of 90.9% and a Kappa coefficient of 0.47. We chose this data set due to two major reasons. First, this data set provides urban land data at short time intervals (i.e., 1992, 1996, 2000, 2006, 2010, and 2016), which can be used to analyze the changes in urban expansion speed. Moreover, small time steps are required to accurately separate different types of urban



**Figure 1.** Analytical framework for urban expansion features during 1992–2016 globally.

development. Otherwise, leapfrog urban land growth could be misclassified as edge-expanding urban land growth because infilling urban land growth could connect leapfrog urban patches with existing urban patches. Second, this data set reflects global urban expansion dynamics from 1992 to 2016 comparably with other data sets (such as the ESACCI, UCL-Geomatics, 2017, and the GHS built-up data set; Pesaresi et al., 2013, 2016). The accuracy of these data sets was evaluated against the GHS built-up data set, the GHS SMOD data set, and the ESACCI data set among 34 selected cities with various socioeconomic conditions based on finer-resolution Landsat imagery. The results showed that the overall accuracy and Kappa for this data set are 0.4%–3.5% and 0.27–0.32 higher than those of the other three data sets (He et al., 2019). In addition, we noticed that recently there was new annual urban expansion data published by Li et al. (2020). To verify the reliability of urban land data used in this study, we examined the correlation between the two data sets at the continental scale, and the correlation coefficient reaching 0.765 ( $p < 0.01$ ). In other words, the trend of urban expansion between the two data sets is comparable. Therefore, we believe that the use of such short time intervals data will not affect our research conclusions.

We used the HydroSHEDS drainage data set developed by the World Wildlife Fund for watershed division. This data set delineated watersheds in a consistent manner at different scales. and a hierarchical sub-basin breakdown was created following the topological concept of the Pfafstetter coding system (terms as HydroBASINS), with a 15" spatial resolution. It has been widely used in watershed-scale analysis, and the results are in good agreement with other commonly used data sets (Lehner & Grill, 2013). We calculated results on multiple levels. First, we calculated the first level (i.e., continental hydrological region) results and compared these results (Table S1) to previous studies using a continental administrative boundary (Gong et al., 2020; Liu et al., 2020). The comparison showed that, although the definition of urban land and studied periods vary between our study and the two previous studies, the trend of urban expansion was consistent. Specifically, they found that the world experienced a large amount of urban expansion, mainly

in Asia and North America; and urban expansion in North America, Europe, and Australia had decelerated (Gong et al., 2020; Liu et al., 2020). Then, we focused on the third-level watersheds as they contain major river basins globally and were commonly adopted by global watershed studies (Grill et al., 2015; Messenger et al., 2016). We further divided the third-level watersheds into endorheic and exoreic watersheds following a previous study (Wang et al., 2018). We also conducted our analyses at the fourth and fifth levels of watersheds.

We further used urban population data obtained from the HYDE 3.2 data set with a spatial resolution of 30" (Klein Goldewijk et al., 2017). We matched population data to data on urban land by selecting the closest year for which data was available, that is, 1990, 2000, 2006, 2010, and 2016. We also used boundaries of cities from the Global Administrative Area Data set (GADM, version 3.4, <https://www.gadm.org/>). We used the second level (city level) boundary of the GADM data set, and it records boundaries of 45,962 cities globally. The spatial resolution of these raster data sets was resampled to 1 km.

## 2.2. Quantifying the Speed of Urban Expansion From 1992 to 2016

Considering the large variations in watershed areas, we used a normalized indicator, the watershed-standardized annual average rate of urban expansion, to compare urban expansion speeds among watersheds (He et al., 2015). The calculation formula is as follows:

$$K_{t_2-t_1} = \frac{\text{Area}_{t_2} - \text{Area}_{t_1}}{S(t_2 - t_1)}$$

where  $K$  is the standardized annual average rate of urban expansion; and  $\text{Area}_{t_1}$  and  $\text{Area}_{t_2}$  represent the urban land area in the watershed in  $t_1$  and  $t_2$ , respectively.  $S$  is the watershed area.  $K$  is the unitless or can be described as a unit of  $\text{km}^2/\text{km}^2$  per year. The larger the  $K$  values are, the faster the urban land expands in the watershed.

To compare urban expansion speed among watersheds, we divided urban expansion speed into five levels: fast, moderately fast, moderate, slow, and decrease according to the mean value and standard deviation of the standardized annual average rate of urban expansion (He, Li, et al., 2017).

## 2.3. Examining Trends in Urban Development Over Time

To identify whether urban expansion within watersheds was accelerating or decelerating, we used an index, called the deceleration factor  $M$ . Since we were concerned about the speed trend in recent years, we compared the last period and the overall period. The formula for this is as follows,

$$M = \frac{K_{10-16}}{K_{92-16}} \times 100\%$$

where  $K_{92-16}$  and  $K_{10-16}$  represent the standardized rate of urban expansion in the two periods of 1992–2016 and 2010–2016, respectively. If  $M$  is less than 100% and equal to or larger than 0%, it indicates that recent urban expansion decelerates. The smaller the deceleration factor is, the faster the urban expansion decelerates, and vice versa. More importantly, we also paid attention to the changing trend of the speed between different short-term intervals. For watersheds with decelerating urban expansion, we further divided them into continuous decelerating watersheds and fluctuant decelerating watersheds. The former experienced continuous declines in urban expansion speeds over the five periods (1992–1996, 1996–2000, 2000–2006, 2006–2010, and 2010–2016), while the rest of decelerating watersheds belong to the latter. If  $M$  is greater than 100%, it suggests that urban expansion accelerated in recent years. It is worth mentioning that, except for the abovementioned categories, a small number of watersheds experienced shrinkage in the urban land area during at least one of the two periods (i.e.,  $K_{92-16} \leq 0$  or  $K_{10-16} \leq 0$ ), and we classified them as the others.

## 2.4. Analyzing the Heterogeneity in Urban Development Within Watersheds

Urban development may vary substantially between the upper, middle, and lower reaches of a watershed, which could result in spatially heterogeneous impacts on regional ecosystems and the environment. It is



imperative to provide such information for policymakers to prepare watershed-scale coordinated plans. To this end, we also measured the heterogeneity of urban expansion speeds within each watershed. Specifically, we quantified urban expansion speed (i.e.,  $K$ ) for each city within a watershed using the city boundaries provided by the GADM data set. Then, we calculated the Gini coefficient of these speeds within each watershed. For this analysis, we used the administrative boundaries rather than finer scale watershed boundaries because the finer scale watershed boundary may include multiple cities and cause incomparability among watersheds. For the calculation at the fourth-level and fifth-level watershed scale, we only included watersheds having at least five cities defined in the GADM data set, because Gini-coefficients for less than five observations are misleading. After the screening, 446 out of 877 fourth-level watersheds and 764 out of 2,274 fifth-level watersheds were left in for analysis.

### 2.5. Analyzing Urban Expansion Mode

Changes in urban expansion mode are closely related to the process of urban development. Existing studies have shown that the mode of urban expansion presents a process of “diffusion first and then aggregation” (Dietzel, Herold, et al., 2005) or a process of structure fragmentation and shape complexity (Guhathakurta, 2003), which depend on the spatial relationship between new urban land patches and existing ones (Liu et al., 2016). We used the landscape expansion index (LEI) to classify urban expansion modes (Liu, Li, et al., 2010) to either leapfrog, edge-expansion, or infilling growth. The equation for LEI is as follows,

$$LEI = \frac{A_0}{A_0 + A_\gamma} \times 100$$

where  $A_0$  is the intersection between the buffer zone around a new urban patch and existing urban land, and  $A_\gamma$  is the intersection of the buffer zone and nonurban land. As the spatial resolution of the urban land data set is 1 km, we first converted all data to vector format and subsequently applied a buffer of 100 m. The value of LEI varies between 0 and 100. When the index is 0, it indicates a leapfrog expansion. When the LEI is between 0 and 50, it represents edge-expansion growth. When the LEI is between 50 and 100, infilling growth occurs. Subsequently, we examined the proportion of urban expansion modes over time.

### 2.6. Investigating Urban Expansion Efficiency

Low-density urban expansion (i.e., urban sprawl) was blamed for its adverse environmental and ecological impacts (R. Ewing & Hamidi, 2015; R. H. Ewing, 2015). Thus, we further used an urban sprawl index, that is, the difference between the average annual rate of urban land and the average annual rate of urban population, to identify urban sprawl (Gao et al., 2016),

$$USI = \frac{Area_{t_2} - Area_{t_1}}{Area_{t_1} \times (t_2 - t_1)} - \frac{UP_{t_2} - UP_{t_1}}{UP_{t_1} \times (t_2 - t_1)}$$

where USI stands for the urban sprawl index, and  $UP_{t_1}$  and  $UP_{t_2}$  represent the urban population in the year of  $t_1$  and  $t_2$ , respectively. Because of the inconsistency in the time range between the urban land data and urban population data, we could only calculate this index for four periods (1992–2000, 2000–2006, 2006–2010, and 2010–2016). In this first period (i.e., 1992–2000), we used the urban population data in 1990 to represent the situation in 1992, and consistently used a 10-year time period.

We divided the watersheds into four types according to the changes in USI over time. Regions with a decline in USIs for all consecutive periods (1992–2000, 2000–2006, 2006–2010, and 2010–2016), are indicated as “continuous decline,” while the opposite is named “continuous increase.” Regions without such clear trends are named “fluctuant decrease” and “fluctuant increase,” depending on whether the last period (2010–2016) was characterized by a USI smaller or larger than the average USI of all four periods, respectively.

We also compared the differences in the abovementioned five perspectives (speed, trend, heterogeneity, mode, and efficiency) of urban expansion between the endorheic and exoreic watersheds.

The five indicators are complementary. The speed of urban expansion and trend in speed are fundamental for characterizing urban expansion at the watershed scale. Urban expansion mode mainly focuses on the relationship between new urban patches and existing urban patches. The heterogeneity of speed can be used to characterize the unevenness of the speed within a given watershed, and the urban sprawl index can further describe the efficiency of urban expansion. Fast urban expansion, strong heterogeneity of urban expansion speed, and high urban sprawl indicate that urban land may manifest in an unsustainable manner in a watershed.

### 3. Results

#### 3.1. Urban Expansion Speed

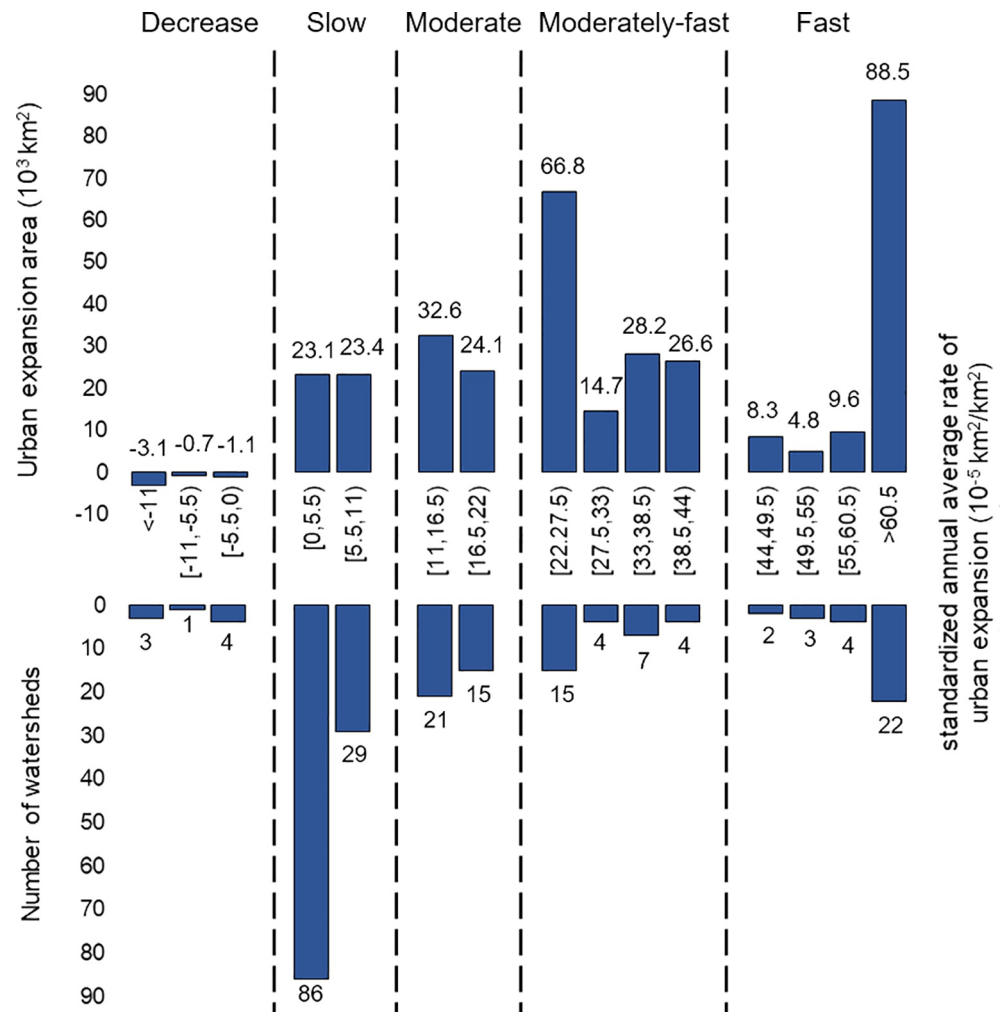
Globally, urban land increased from  $2.75 \times 10^5 \text{ km}^2$  in 1992 to  $6.21 \times 10^5 \text{ km}^2$  in 2016, a 1.3-fold increase (or  $K = 11.3 \times 10^{-5} \text{ km}^2/\text{km}^2$  Table S1). The expanded urban land was mainly concentrated in Asia, North America, and Europe. Urban land in these three continental watersheds expanded by  $2.83 \times 10^5 \text{ km}^2$ , accounting for 74.0% of the global urban expansion. In addition, Asia and North America's urban land expanded the fastest. The average annual rates were  $21.99 \times 10^{-5} \text{ km}^2/\text{km}^2$  and  $20.62 \times 10^{-5} \text{ km}^2/\text{km}^2$ , or 1.9 times and 1.8 times the global average, respectively. These findings are generally consistent with previous global analyses using other urban land data sets and administrative boundaries (Gong et al., 2020; Liu et al., 2020).

Urban land expansion among third-level watersheds is distributed rather unequally. Among the 220 watersheds, most experienced a slow speed of urban expansion (Figure 2). Specifically, the average annual rate of urban expansion in 115 watersheds (or 52.3% of all watersheds) was slow. The standardized urban expansion rate of these watersheds was between 0 and  $11 \times 10^{-5} \text{ km}^2/\text{km}^2$  per year, which is lower than the global average rate of  $11.31 \times 10^{-5} \text{ km}^2/\text{km}^2$  per year. In terms of their spatial distribution, these slow expanding watersheds are mainly found in Africa, central and western Australia, northern South America, and Siberia (Figure 3). Consistently, the vast majority of all urban expansion is included in a small number of moderately fast and fast-growing watersheds (30 and 31 watersheds, respectively; Figure 2). The moderately fast-growing watersheds included a total urban expansion of  $1.36 \times 10^5 \text{ km}^2$ , accounting for 39.4% of the global total. The standardized average annual rates of these watersheds range from  $11 \times 10^{-5} \text{ km}^2/\text{km}^2$  to  $44 \times 10^{-5} \text{ km}^2/\text{km}^2$ , which is larger than the global average. In terms of spatial distribution, these moderately fast-expanding watersheds are mainly distributed in southern Asia, northwestern North America, and southeastern South America (Figure 3). In addition, the 31 fast-expanding watersheds included a combined urban expansion area of  $1.11 \times 10^5 \text{ km}^2$ , accounting for 32.1% of the global total. The standardized rates of these watersheds range between 4 and 150 times the global average. Fast-expanding watersheds are mainly distributed in eastern Asia, Europe, North America, and central South America (Figure 3). The results of the 877 fourth-level watersheds and 2,274 fifth-level watersheds are similar, with more than 50% of watersheds experiencing a slow urban expansion speed and more than 70% of expanded urban land areas concentrating in a smaller number of fast and moderately fast growing watersheds (Table S2, Figures S1 and S2).

The speed of urban expansion was slower in endorheic watersheds than in exoreic watersheds (Table 1). In the past 24 years, the average annual rate of urban expansion in endorheic basins was  $3.77 \times 10^{-5} \text{ km}^2/\text{km}^2$ , which was only approximately 1/4 of the rate ( $13.41 \times 10^{-5} \text{ km}^2/\text{km}^2$ ) in the exoreic basin. It is also worth noting that the standard deviation of the average annual rate of urban expansion in endorheic basins ranged from 3.8 to 13.8 during the five periods, whereas those in exoreic watersheds were between 28.1 and 95.7. This indicates that the variation in urban expansion speeds among endorheic watersheds was much smaller than that in exoreic watersheds. Moreover, although urban expansion in some endorheic watersheds, such as Saudi Arabia and Algeria's Sharif watersheds, was still accelerating, no endorheic watershed had an urban expansion speed reaching up to the level of moderately fast among global watersheds.

#### 3.2. Deceleration of Urban Expansion

From 1992 to 2016, urban expansion decelerated (Table 1). The global average annual rate of urban expansion declined gradually from  $22.26 \times 10^{-5} \text{ km}^2/\text{km}^2$  in 1992–1996 to  $14.41 \times 10^{-5} \text{ km}^2/\text{km}^2$  in 1996–2000, and to  $5.90 \times 10^{-5} \text{ km}^2/\text{km}^2$  in 2010–2016. The  $M$  factor is 52.2%, which suggests the average annual rate of

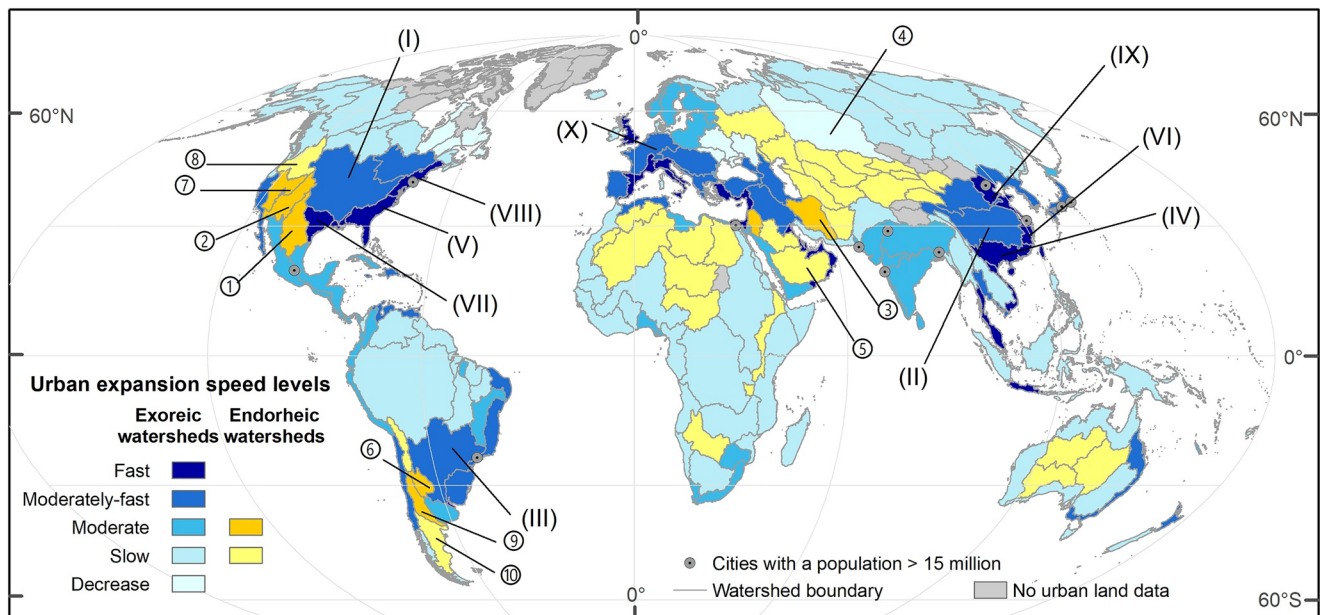


**Figure 2.** Urban expansion amount and speed among global watersheds. *Note.* Urban expansion speed as divided according to the mean value and standard deviation of the standardized annual average rate of urban expansion. The five categories of speed were determined by the global average speed ( $11.3 \times 10^{-5}$ ), and its twofold ( $22.6 \times 10^{-5}$ ), and fourfold ( $45.2 \times 10^{-5}$ ).

urban expansion in the last 6 years was slightly more than half of that in the past 24 years. Urban expansion in all continental hydrological regions slowed down. Among them, Europe, the Arctic of North America, and Australia decelerated the most. Their deceleration factors  $M$  are 23.8%, 30.0%, and 50.5%, respectively (Table S1), which are all lower than the global average (52.2%). These results are also consistent with previous findings at continental scales (Güneralp et al., 2020; Liu et al., 2020).

Most of the third-level watersheds showed a considerable slowdown in urban expansion. Among the 220 watersheds, the urban expansion of 154 slowed down (Figure 4) as their standardized urban expansion rates in 2010–2016 were smaller than those in 1992–2016. Among 154 watersheds, urban expansion in 29 watersheds exhibited a continuous deceleration. These watersheds are mainly distributed in coastal areas, such as the Gulf of Mexico–North Atlantic Coast and Pearl River. While the other 125 watersheds experienced fluctuant deceleration of urban expansion in our 24-year study period. The other 66 watersheds can be divided into 37 watersheds with accelerating urban expansion during the last 6 years, comparing the average urban expansion speed in the last 24 years, and 29 watersheds with shrinkage in urban land areas. The situations at the fourth-watershed and fifth-watershed scales are similar, with more than 60% of watersheds exhibiting a slowdown in urban expansion speed (Table S3, Figures S3 and S4).





**Figure 3.** Comparison of urban expansion speeds between the endorheic and exoreic watersheds. Note: (I)–(X) and ①–⑩ are the top 10 exoreic endorheic and endorheic watersheds for the total areas of urban expansion, respectively. (I) Mississippi River Basin; (II) Yangtze River Basin; (III) La Plata River Basin; (IV) Pearl River Basin; (V) Gulf of Mexico–North Atlantic Coast; (VI) China Coastal Basin; (VII) Gulf of Mexico coast; (VIII) North Atlantic coast; (IX) Haihe River Basin; (X) Rhine River Basin. ① Grand River Basin; ② Colorado River Basin in North America; ③ Central Iran Basin (Karon River Basin); ④ Sir River Basin; ⑤ Arabian Peninsula; ⑥ Argentina Macchiqueta; ⑦ Great Basin of the United States; ⑧ Columbia River Basin; ⑨ Colorado Basin in South America; and ⑩ South Argentina–South Atlantic Coast; The maximum urban expansion speed of the endorheic watershed was  $20.98 \times 10^{-5}$ , and the minimum was  $0.03 \times 10^{-5}$ . Therefore, there are only two speed levels for endorheic watersheds.

Urban expansion in both endorheic and exoreic watersheds showed a decelerating trend (Table 1, Figure 4), with average deceleration factors below 100%. The deceleration factor of endorheic watersheds is 58.5%, slightly higher than the value of exoreic watersheds (51.6%). This suggests that urban expansion in endorheic watersheds decelerated slower than that in exoreic watersheds. In addition, urban expansion in a few endorheic watersheds did not slow down or even accelerated. For example, the deceleration factors of the Algeria Sharif River watershed and Saudi Arabia watershed are both larger than 200%.

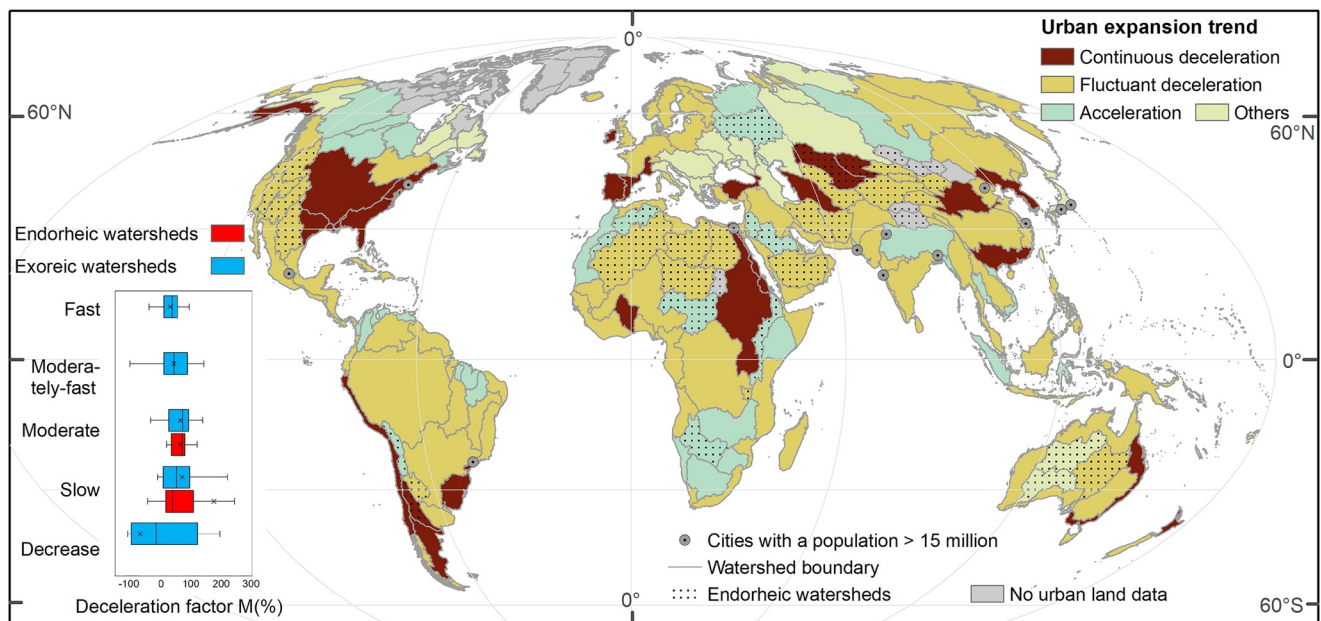
### 3.3. Heterogeneity in Urban Development Within Watersheds

Overall, the unevenness of urban expansion speeds within watersheds increased over time. Among the 220 watersheds, the Gini coefficient of the urban expansion speeds grew from 0.63 in the first period of 1992–1996 to 0.76 in the second period of 1996–2000, and remained at 0.76 during the following three

**Table 1**  
*Trend and Heterogeneity of Urban Expansion Speed at the Watershed Scale*

Standardized annual average rate of urban expansion ( $10^{-5} \text{ km}^2/\text{km}^2$ )	1992–1996	1996–2000	2000–2006	2006–2010	2010–2016	1992–2016
All the watersheds ( $M = 52.2\%$ )	22.3 (89.3)	14.4 (66.0)	7.3 (40.2)	11.3 (61.4)	5.9 (25.8)	11.3 (43.8)
Endorheic watersheds ( $M = 58.5\%$ )	6.8 (13.8)	5.30 (9.8)	2.3 (4.7)	3.8 (3.8)	2.2 (4.3)	3.8 (6.0)
Exoreic watersheds ( $M = 51.6\%$ )	26.6 (95.7)	17.0 (71.1)	8.7 (43.5)	13.4 (44.4)	6.9 (28.1)	13.4 (47.0)
Gini coefficient						
All the watersheds	0.63 (0.25)	0.76 (0.19)	0.76 (0.20)	0.76 (0.21)	0.76 (0.19)	0.64 (0.23)
Endorheic watersheds	0.59 (0.29)	0.73 (0.22)	0.74 (0.20)	0.77 (0.19)	0.75 (0.23)	0.65 (0.25)
Exoreic watersheds	0.64 (0.24)	0.77 (0.19)	0.77 (0.20)	0.76 (0.21)	0.77 (0.18)	0.63 (0.22)

*Note.* The number inside the brackets is the standard deviation.

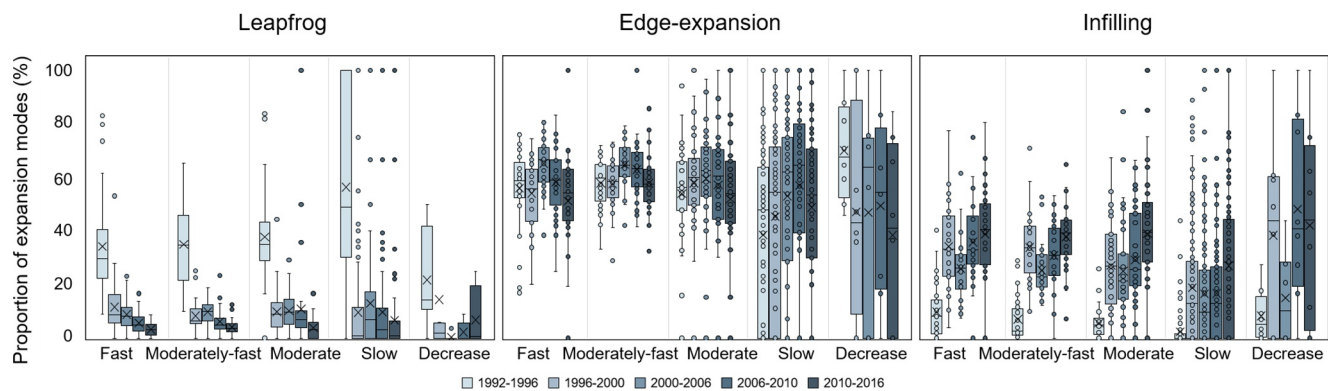


**Figure 4.** Comparison of urban expansion trends between the endorheic and exoreic watersheds. *Note.* The classification of the four urban expansion trends can be found in the Methods section, and all the acceleration ones belong to fluctuant acceleration.

periods (Table 1). When the 220 watersheds are further divided into 877 fourth-level and 2,274 fifth-level watersheds, the heterogeneity of urban expansion speeds shows a similar uneven pattern (Table S4). Specifically, the Gini coefficients for the fourth-level and fifth-level watersheds increased from 0.63 in 1992–1996 to 0.73 and 0.77 in 2010–2016, respectively.

Urban land expanded more unevenly in exoreic watersheds. In the past three periods, the Gini coefficient of the urban expansion speeds in exoreic basins rose from 0.64 in 1992–1996 to 0.77 in 1996–2000, and fluctuated between 0.76 and 0.77 in the following periods. In contrast, the Gini coefficient in endorheic basins rose from 0.59 to 0.75, which was lower than the corresponding values in exoreic watersheds in all periods.

It is worth noting that the gap in uneven urban development between exoreic and endorheic basins narrowed over time, with the difference in Gini coefficient decreasing from 0.05 in 1992–1996 to 0.02 in 2010–2016. This suggests that urban expansion within endorheic basins followed the uneven path of exoreic watersheds, with urban development increasingly concentrated in a few cities in each watershed. Taking an endorheic watershed, the Colorado River watershed, as an example, urban land expanded unevenly between the upper and lower reaches of this watershed. In the middle and lower reaches of this watershed (i.e., Sonora and Utah), urban land expanded rapidly, and the average annual rate of the urban expansion rate from 2010 to 2016 is 3.93 times and 1.39 times that from 1992 to 2000, respectively. In contrast, the average annual rate of urban expansion in the upper reaches is smaller, leading to uneven growth within the watershed. However, in many exoreic basins with large-scale urban expansion, the Gini coefficient of the urban expansion rates decreased, which implied a more even distribution of urban development over different cities. Taking the Yangtze River watershed as an example, the Gini coefficient of its urban expansion rates decreased from 0.92 during 1992–2000 to 0.89 during 2010–2016. Among them, the urban expansion rates of upstream middle-sized cities such as Chongqing and Guizhou from 2010 to 2016 are 1.76 and 1.96 times those from 1992 to 2000, respectively. In large cities downstream, such as Shanghai and Nanjing, urban expansion rates decelerated to 0.53 and 0.56 times the original rate, respectively. Among the 35 watersheds where the Gini coefficient of the urban expansion rate decreased, there were only 4 endorheic watersheds, while 31 were exoreic watersheds. This finding also suggests that endorheic watersheds were still at the stage of rapid urban expansion in existing large cities.



**Figure 5.** Proportions of urban expansion modes among watersheds.

### 3.4. Urban Expansion Mode

The leading mode of urban expansion was edge expansion. From 1992 to 2016, the global area of urban expansion resulting from edge expansion was  $2.03 \times 10^5 \text{ km}^2$ , accounting for 58.8% of the total expanded urban area. In contrast, infilling and leapfrog expansion accounted for  $8.06 \times 10^4 \text{ km}^2$  and  $6.19 \times 10^4 \text{ km}^2$ , respectively, or 23.3% and 17.9% of the total urban expansion. From 1996 to 2016, the proportion of edge expansion in all 220 watersheds exceeded 50%, between 56.8% and 60.7% (Figures 5 and S5). Infilling and leapfrog expansion represented 16.4%–27.0% and 15.1%–22.5% of all urban expansion within watersheds, respectively.

From 1992 to 2016, at the third-level watershed scale, leapfrog urban expansion decreased and infilling urban expansion increased (Figure 5). The average proportion of leapfrog urban expansion dropped from 34.7% in 1992–1996 to 10.9% in 2000–2006 and then to 4.3% in 2010–2016. Correspondingly, the proportion of infilling urban expansion rose from 9.4% to 23.3% and then to 41.7% in the same periods. These findings suggest that urban development followed a “diffusion first and then aggregation” process (Dietzel, Herold, et al., 2005; Dietzel, Oguz, et al., 2005). The results at the fourth-level and fifth-level watersheds also support these findings (Table S5).

The mode of urban expansion is dominated by edge expansion in both endorheic and exoreic watersheds (Table S6). From 1992 to 2016, the proportions of edge-expansion urban areas in the exoreic watersheds and endorheic watersheds reached 59.1% and 55.8%, respectively. In addition, both the endorheic and exoreic river watersheds show a trend of decreasing leapfrog expansion and increasing infilling expansion (Table S6). The proportion of leapfrog expansion in the exoreic basins dropped from 34.6% in 1992–1996 to 10.9% in 2000–2006 and then to 4.3% in 2010–2016, a total decrease of 30.3%. The proportion of leapfrog expansion in the endorheic basins dropped from 35.8% to 10.0% and then to 4.3%, which represents a total drop of 31.5%. Correspondingly, the proportion of infilling expansion in exoreic basins increased from 9.6% to 22.5% and then to 40.8%, which represents a total increase of 31.2%. The total rise in endorheic river watersheds reached 42.5%. In other words, the degrees of reduction in leapfrog expansion and increase in infilling expansion are stronger in endorheic basins than in exoreic basins.

### 3.5. Urban Expansion Efficiency

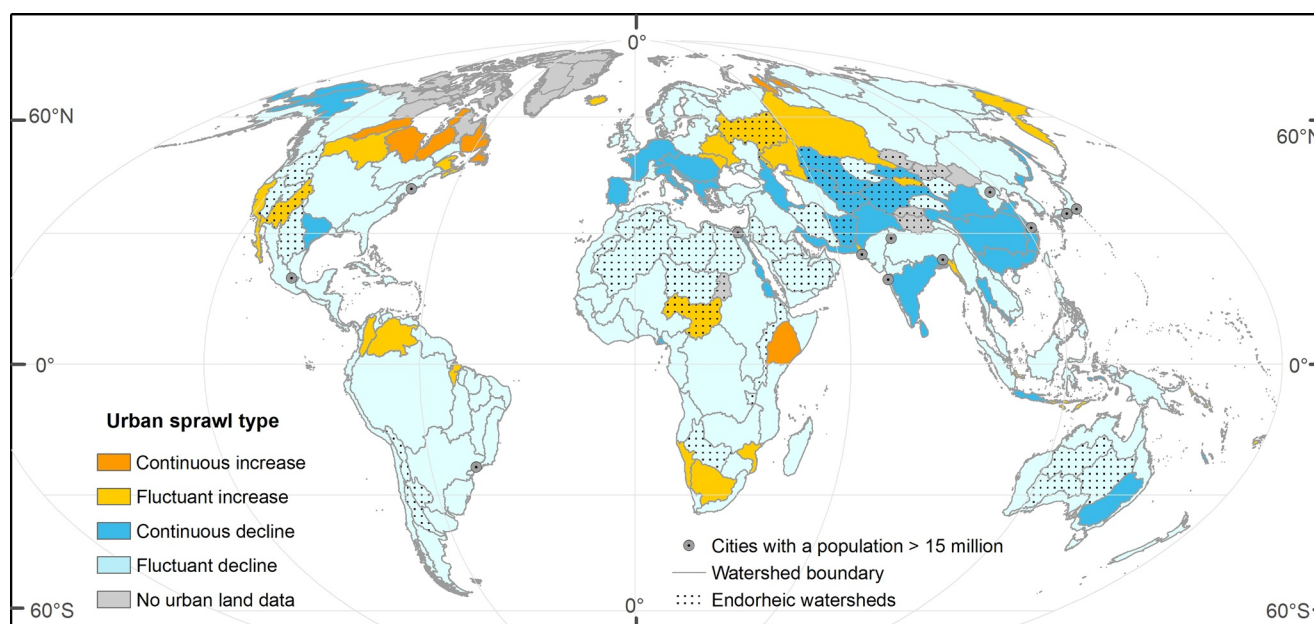
In the past 24 years, urban land grew faster than the urban population in 75.9% of the world's watersheds, showing a trend of low-density urban land expansion (or urban sprawl). During this period, the global urban sprawl index was 0.109. This is consistent with existing studies. For example, Güneralp et al. (2020) found that global urban land increased faster than the population from 1970 to 2010, causing the global urban population density to continue to decline. Comparing the endorheic and exoreic watersheds, the trend of low-density urban sprawl in the endorheic watersheds is more prominent, with an urban sprawl index (0.139) 1.3 times that of the exoreic watersheds (0.103). In terms of the proportion of watersheds, 29 out

**Table 2**  
*Changes in Urban Sprawl Among Watersheds Globally From 1992 to 2016*

		1992–2000	2000–2006	2006–2010	2010–2016	1992–2016
All watersheds ( $n = 220$ )	Number of watersheds with an USI > 0	166	120	151	100	167
	Average USI	0.181	0.009	0.016	0.007	0.109
	Standard deviation of USI	0.280	0.047	0.039	0.095	0.210
Endorheic watersheds ( $n = 36$ )	Number of watersheds with a USI > 0	26	22	18	14	29
	Average USI	0.225	0.004	0.008	−0.001	0.139
	Standard deviation of USI	0.426	0.021	0.032	0.036	0.290
Exoreic watersheds ( $n = 184$ )	Number of watersheds with a USI > 0	140	98	133	86	138
	Average USI	0.172	0.010	0.018	0.009	0.103
	Standard deviation of USI	0.240	0.050	0.041	0.103	0.191

of 36 endorheic watersheds (80.6%) exhibited low-density sprawl (USI > 0), which is also higher than the proportion (75.0%, 138/184) among exoreic watersheds.

In recent years, urban sprawl in global watersheds has shown a downward trend (Table 2). The number of watersheds exhibiting urban sprawl (USI > 0) dropped from 166 in 1992–2000 to 151 in 2006–2010 and then to 100 in 2010–2016, while the average USI decreased from 0.181 to 0.009 and then to 0.007, accordingly. Results among the fourth-level and fifth-level watersheds also supported this trend, with average USI declining from 0.375 and 0.269 in 1992–2000 to 0.006 and 0.006 in 2010–2016, respectively (Table S7). This was also consistent with an existing study that showed that the urban population in large cities globally was growing faster than the corresponding increase in urban land (Sun et al., 2020). The declining trend in urban sprawl is more prominent in endorheic watersheds than exoreic watersheds. Specifically, the average USI in endorheic watersheds decreased by 0.226 between 1992–2000 and 2010–2016. By contrast, the decrease in average USI in exoreic watersheds during the same period was 0.163. Although urban sprawl among global watersheds slowed down, it still manifested in a few endorheic watersheds, such as the Colorado river basin in the United States, Volga river basin in Russia, and Ili river basin (Figure 6). Their USIs increased by 0.015, 0.006, and 0.076 between 1992–2000 and 2010–2016, respectively.



**Figure 6.** Comparison of urban land and urban population growth rates in watersheds. Note: The classification of the four urban sprawl types can be found in Section 2.



## 4. Discussion

### 4.1. The Watershed Perspective for Understanding the Impacts of Urban Development

The watershed-scale results in this study not only corroborated previous findings, but also shed light on understanding the dynamics of urban expansion at the watershed scale. First, we found that approximately 40% of the total urban expansion is located in only a few moderately fast-expanding watersheds distributed in northwestern North America (e.g., Mississippi River Basin), eastern Asia (e.g., Yangtze River basin), and southeastern South America (La Plata River Basin). While we know from previous studies that most urban expansion is concentrated in the United States, China, and Europe (Liu et al., 2020; Seto et al., 2011), this study shows that it is in fact concentrated in only a few watersheds, which are mostly within these countries and regions. Yet, there are also a number of other watersheds with relatively little urban expansion in these regions.

Second, our results also supported the “diffusion-aggregation” dynamics of urban expansion found by previous researchers (Dietzel, Oguz, et al., 2005; Wu et al., 2011). At the watershed scale, urban expansion originates from a few urban cores. As the area of urban core grows, new urban patches will emerge in a scattered manner around the urban cores (i.e., diffusion process or leapfrog expansion). This pattern was observed in each individual watershed, showing that it is rather generic. While the urban cores expand outward, they are connected with these newly emerged urban patches (i.e., aggregation process or infilling expansion). Research at the global scale also found that urban expansion conforms to this diffusion-aggregation process (Liu et al., 2016).

Third, we found that 154 out of the 220 tertiary watersheds exhibited a trend of deceleration in urban expansion speed. This trend is more evident in developed economies, such as the Mississippi River basin, the North Atlantic coast basin in North America, and the Rhine River basin in Europe, than the developing economies, for example, in the Yangtze River basin in East Asia and the La Plata River basin in South America. In other words, at the watershed scale, the urban expansion speed of most of the world's watersheds also conforms to an S-shaped Northam curve of urbanization, where the urbanization process accelerates first and decelerates thereafter (Northam, 1975). This deceleration in developed economies could be a good news for reducing the adverse in situ impacts of urban expansion, such as habitat loss and changes in the hydrological and biogeochemical cycles. However, the distant (or tele-coupled) impacts of urban expansion (such as the consumption of embodied carbon and virtual water) imposed by the developed economies on the developing economies cannot be ignored (Wiedmann & Lenzen, 2018; Xu et al., 2020).

Endorheic watersheds differ significantly from exoreic watersheds in terms of their expansion speed and inequality of expansion within these watersheds (*T*-test result in Table S8). More specifically, urban expansion speed and extent in endorheic watersheds lagged behind the counterparts in exoreic watersheds for the last two decades. Meanwhile, our comparison of urban expansion also highlighted the sprawling pattern between the endorheic and exoreic watersheds was not significantly different (Table S8). It suggests that endorheic watersheds' urban expansion is catching up and following the trends of exoreic watersheds in a sprawling manner. Although the average USI in endorheic watersheds was 1.3 times that of exoreic watersheds, and the sprawling trend of urban expansion was particularly prominent in a few endorheic watersheds, such as the Colorado river basin in the United States, the Volga river basin in Russia, and Ili river basin. However, most endorheic watersheds spatially overlap with dryland, which are less endowed with water resources and more vulnerable to anthropogenic stresses and climate changes than exoreic watersheds (Berdugo et al., 2020; Middleton & Sternberg, 2013; Reynolds et al., 2007). This implies that a trend of urban expansion could exert greater ecological and environmental impacts on these endorheic watersheds, and threaten their sustainability. The drivers of such sprawling urban development are often region-specific, and include, for example, suburbanization and automobile dependency (Hamidi & Ewing, 2014; Kirillov et al., 2019), population migration and housing prices (Bae & Richardson, 2017), and tourism development (Liu, Zhang, et al., 2010). Correspondingly, in these endorheic watersheds, it is necessary to form place-based assessments to control sprawl. On the one hand, the urban development policy must control the rapid growth of urban land; on the other hand, it must encourage infilling expansion and the vertical growth of buildings to increase the utilization efficiency of urban land.



#### 4.2. Implications of Watershed-Scale Urban Expansion

One important potential reason for the deceleration of urban expansion is the slowdown in socio-economic development and population growth. Previous studies found that socio-economic and population growth are the main driving factors for urban land expansion (Seto et al., 2011). Recently, the global GDP and urban population growth rate have gradually declined (International Monetary Fund, Research Dept., 2011), which were associated with urban expansion deceleration.

Urban expansion and its speed are important proxies for anthropogenic activities. Globally, rivers and river basins were increasingly affected by anthropogenic stresses (Best, 2019), ranging from dam construction (Zarfl et al., 2015), pollution (Mekonnen & Hoekstra, 2015; Vörösmarty et al., 2010), anthropogenic hydrological change (Nienhuis et al., 2020), and anthropogenic climate change (Winsemius et al., 2016). In this context, researchers have developed a number of fine-scale, long-term databases for examining the dynamics of global watersheds. For example, the HydroATLAS V1.0 database includes 56 variables and 281 attributes for hydrological, physiographic, climatic, land cover, soil, geological and anthropogenic changes among global watersheds and rivers (Linke et al., 2019). Similar databases were also compiled by collaborations of international research groups based on the HydroSHEDS drainage data set (Barbarossa et al., 2018; Domisch et al., 2015). However, most of these databases only include a snapshot of urban land cover data. Thus, using these databases to estimate the anthropogenic stresses on global watersheds may lead to biased results. Therefore, it is imperative to include long-term, multiple temporal, and consistent urban expansion information for global watersheds. Our study provides such information for the global watersheds consistently divided by the HydroSHEDS data set, and can be further utilized to investigate the integrated impacts of the changes in human-environment systems on global and regional watersheds.

The impacts of urban expansion are not restricted by city boundaries. Previous studies have found that urban activities and urban expansion could incur heat islands (Manoli et al., 2019), acid islands (Du et al., 2015), and fog islands (Zhu et al., 2020), which are not constrained by city boundaries and can reach up to 10–60 km away from the periphery of existing built-up land. In addition, urban expansion can alter watershed-scale hydrological and biogeochemical cycles, and bring water, air, and soil pollutants along surface water, groundwater, and road networks across and beyond the watershed (Best, 2019; McDonald et al., 2020). Consequently, regulating and addressing these ecological and environmental impacts needs coordinated efforts from multiple institutions and departments at the watershed scale. The traditional territorially based urban governance system, which is confined by political boundaries, has been continuously challenged by the “silo effects” that stemmed from problems of inter-jurisdictional, cross-level, and inter-departmental fragmentation. As a response, “rescaling to watersheds” has been seen as an act reflective of the failure of integration and myopic decision-making (Cohen, 2012). The “watershed approach,” which indicates a paradigmatic shift from political boundaries to hydrological ones, has been widely prescribed for carrying out more ecologically meaningful forms of governance (Davidson, 2011). Therefore, quantifying urban expansion at the watershed scale could inform policymakers to manage these ecological and environmental issues and form sustainability-oriented planning. Although it is very important to form urban sustainable planning at the watershed scale, it is still a challenge to collect data, mobilize public participation, achieve integration of decision-making across watersheds due to the mismatch between administrative boundaries and watershed boundaries (He & James, 2021).

#### 5. Conclusions

Global urban expansion is decelerating at the watershed scale from 1992 to 2016. The average annual rate of urban expansion dropped from  $22.3 \times 10^{-5} \text{ km}^2/\text{km}^2$  per year in 1992–1996 to  $5.9 \times 10^{-5} \text{ km}^2/\text{km}^2$  per year in 2010–2016, which equals a decrease of 74%. From the perspective of expansion modes, edge expansion was the dominant mode and accounted for 59% of all urban expansion and generally observed patterns followed a trend of “diffusion first and then aggregation.” The proportion of leapfrog expansion dropped from 35% during 1992–1996 to 4% during 2010–2016, while the proportion of infilling expansion increased from 9% to 42%.

Urban expansion in endorheic watersheds lagged behind that in exoreic watersheds. The average annual rate of urban expansion in endorheic watersheds was  $3.8 \times 10^{-5} \text{ km}^2/\text{km}^2$  per year during the study period,

which is only approximately 1/4 of the corresponding value ( $13.4 \times 10^{-5} \text{ km}^2/\text{km}^2$  per year) in the exoreic watersheds. Moreover, differences between endorheic and exoreic watersheds in heterogeneity of urban development, as expressed in the Gini coefficient decreased. This implies that urban expansion in endorheic watersheds was still at the stage of rapid growth in few large cities, while developments in exoreic watersheds became gradually more spread over different cities.

Urban land increased faster than the urban population in approximately 75% of all the watersheds globally. Although such trend toward low-density development became less prominent in recent years for both endorheic and exoreic watersheds, urban sprawl in a few endorheic watersheds was still evident, such as in the Colorado river basin, the Volga river basin, and Ili river basin. In these watersheds, it is necessary to control the low-density growth of urban sprawl and encourage the improvement of the efficiency of urban land use.

First, we found that the vast majority of urban expansion was concentrated in several watersheds. This finding can enrich existing national-scale research results, that is, the hot spots for urban expansion were identified at the watershed scale. Second, we further measured the differences in urban expansion between endorheic and exoreic watersheds. It suggested that endorheic watersheds' urban expansion was catching up and following the trends of exoreic watersheds in a sprawling manner. This is very important for the planning and management of endorheic basins with fragile ecological environments.

## Data Availability Statement

Data sets for this study are available in online repositories and in-text data citation references. Global urban land from 1992 to 2016 was available from an online repository (<https://doi.pangaea.de/10.1594/PANGAEA.892684>). Global watershed boundaries are from HydroSHEDS drainage data set and can be downloaded from <https://hydrosheds.org>. Gridded urban populations are from HYDE 3.2 data set and are available in Klein Goldewijk et al. (2017). City boundaries are downloaded from the Global Administrative Area Data set (GADM, version 3.4, <https://www.gadm.org/>).

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